 《Review》

Biofeedback Therapy in Rehabilitation Medicine : Principles and Practice

Yasutomo OKAJIMA,*¹ Naoichi CHINO,*² Akio KIMURA*²

Historical Overview

The term "biofeedback" was coined as an abbreviation for "biological feedback." It connotes that human beings can perceive and control covert physiological processes through special instrumentation. Patients with neurological dysfunction may be unable to feel some of the processes that normal persons can feel. Furthermore, human beings even with normal sensory system have many processes which are not normally sensed in any way. Biofeedback equipment detects such processes and transforms them into obvious signals. Basmajian in Canada and his colleagues in the U.S.A. are pioneer physicians conducting research on biofeedback treatment for patients in the field of rehabilitation medicine. In 1960s Basmajian³⁾ showed how exquisitely a single motor unit recorded from indwelling wire electrodes in the muscle can be controlled by the use of myoelectric signals displayed on the oscilloscope and also those from the speaker. Concentrating upon the myoelectric activities on the monitors, one can activate a single motor

unit in isolation and regulate the firing rate of the unit. This technique has been gaining wider recognition since the use of wire or needle electrodes was replaced by that of surface electrodes which are easily applicable to daily rehabilitation training. Although the use of surface electrodes abandons skilled control of the motor unit, it suffices for ordinal use of clinical electromyographic (EMG) biofeedback in treatment of the patients with motor dysfunction.

One can strengthen weakened muscle trying to increase visual and acoustic signals from the muscle. Motor drive or volitional firing of the motor units can be reinforced by concurrent perception of outcome of the contraction effort. Biofeedback to augment muscle strength is clinically employed for the treatment of muscle atrophy following fracture, ligament injury, or nerve surgery, and also for neuromuscular re-education of the patient with upper motoneuron damage such as stroke, traumatic brain injury, and cerebral palsy. On the other hand, one can also suppress or relax overactive muscle by attempting to reduce the myoelectric signals. Muscle relaxation by use of EMG predates

Received June 24, 1997

リハビリテーション医学におけるバイオフィードバック：理論と実際

*¹ Department of Rehabilitation Medicine, Keio University Tsukigase Rehabilitation Center/380-2 Tsukigase, Amagi-yugashima, Takata-gun, Shizuoka 410-32, Japan

岡島康友：慶應義塾大学月が瀬リハビリテーションセンター/〒410-32 静岡県田方郡天城湯ヶ島月ヶ瀬 380-2

*² Department of Rehabilitation Medicine, Keio University School of Medicine/35 Shinanomachi, Shinjuku-ku, Tokyo 160, Japan

千野直一, 木村彰男：慶應義塾大学医学部リハビリテーション医学教室/〒160 東京都新宿区信濃町 35

Key words: biofeedback (バイオフィードバック), EMG (筋電図), motor learning (運動学習), treatment (治療), stroke (脳卒中)

evolution of biofeedback in the field of rehabilitation medicine. It was first introduced by Jacobson²⁴⁾ in 1933, who found elevated muscular activities, even at rest, in a patient with chronic colitis, that was eventually alleviated by the training using EMG signals. This leads to later evolution of relaxation therapy for musculoskeletal pain and stress-related disorders. In a rehabilitation setting, it is being utilized to reduce spasticity and dystonic movement due to central nervous system disorder.

Biofeedback and Motor Learning

Feedback of movement or action outcome, either covert or overt for a patient, is not unusual in rehabilitation scenes. It is given verbally by physical and occupational therapists as knowledge of results (KR). KR is defined as the extrinsic information about task success provided to the patient after the movement or action has been completed. It is an essential component of training strategy by which patients learn how to move or act in various environmental settings. In the initial training phase usually, therapists give frequent verbal guidance as they go along. With practice and training, patients rely more and more on their proprio- or interoceptive cues, and are able to achieve better movement control without therapist's verbal cues. Thus, movement or action is acquired. Motor learning aided by biofeedback technique is similar to that by verbal instruction. However, biofeedback is given in quantitative and immediate manner while verbal instruction is rather qualitative and is given after the movement is completed. Furthermore, biofeedback is definitely superior to the verbal instruction in that instrumentation for the biofeedback enables patients to sense minute physiological changes that both therapists and patients can not normally notice.

As is the same as conventional training by therapists, efforts should be made to direct patients' attention from biofeedback equipment to their interoception. Although biofeedback improves motor performance, reliance only

upon the equipment makes it difficult for the patients to accomplish motor learning. Patients' motor performance after biofeedback is often poorer than that without biofeedback training when biofeedback signals are turned off.⁵⁾ Therefore, training sessions without biofeedback should be interpolated into biofeedback training for better motor learning.⁴⁶⁾

Therapeutic efficacy of biofeedback is determined by improved functional capability. Increase of EMG signals does not necessarily mean functional improvement. It should be evaluated by improvement in terms of range of motion, muscle strength, manual function, ambulatory capability, etc. Therefore, biofeedback treatment is ideally targeted not on improvement of movement but on restoration of action useful for daily livings. Increased EMG activity in tibialis anterior muscles attained by biofeedback training in sitting position does not always improve gait pattern in stroke patients. Training should preferably be done while patients are actually walking.³⁴⁾

Sensory information is fed back to correct movement through the neural circuit responsible for comparing the target with the actual movements. The somatosensory cortex, receiving proprioceptive information of the ongoing body movement, modulates activities of the motor cortex through the neural connection via association cortex. However, considering the fact that it takes at least 20 msec for the proprioceptive information to reach the primary somatosensory cortex, every human movement becomes inevitably slow if feedback loops are always involved for establishing motor control. For faster and skilled movements, one may need feedforward control mechanism. However, feedforward mechanism alone does not explain how skillful movements are developed as a result of motor learning.

Both feedback and feedforward mechanisms may play a role to acquire skillful movements and to adapt the motor program to changing environment. Suppose handwriting of an alphabet "a." One can write it vertically on a wall or horizontally in a notebook quite similarly in

shape. However, sequence and magnitude of muscle activation in the arm and hand may differ between these two situations. In other words, a variety of solutions for possible sequence and magnitude of muscle activation can be provided according to environmental changes by the motor scheme for writing the same alphabet. The precess to find such solutions is called "inverse problem solving." If one try to write the alphabet while watching the writing path in the mirror, one may need quite a different motor scheme to establish his or her own style of writing. One may use the difference between the estimated and the actual motor commands as an error signal to develop another solution of the inverse problem.

The feedback-error-learning scheme proposed by Kawato,²⁶⁾ a computational theory of supervised motor learning, is acknowledged as a sophisticated motor-control model in which both feedforward and feedback commands are fed to the motor system. Cerebellar cortex works as a feedforward controller solving the inverse problem for an aimed movement. Output from the motor cortex is conveyed not only to the spinal motoneuron directly but also to the cerebellar cortex via brain stem nuclei. Purkinje cells in the cerebellar cortex provide feedforward command to the motor cortex via thalamic nuclei. Motor cortex works as a transducer of the feedforward command originating from Purkinje cells, and also works as a feedback controller receiving information from sensory and association cortices. Biofeedback using auditory and visual signals may affect the motor command through the neural circuit in the association cortex (Fig. 1). Hence, changes of the feedforward system in the cerebellum.

Brain damage may disrupt or alter neural circuits for a motor control. Biofeedback treatment is considered as implementing new forms of circuits which were previously unused. Patients improve performance of the specific movement with continued biofeedback training. After establishing new circuits for the movement, possibly in the cerebello-cerebral com-

Fig. 1 Biofeedback and motor learning

Output from the motor cortex is projected both to the spinal motoneuron and to the cerebellar cortex via brain stem nuclei. Purkinje cells in the cerebellar cortex provide feedforward command to the motor cortex via thalamic nuclei. Motor cortex works under the influence of both feedforward command originating from Purkinje cells and feedback information from sensory and/or association cortices. Auditory and visual feedback may affect the motor command through the neural circuit in the association cortex.

plex, patients can complete the movement task without relying on the visual or auditory information given by the biofeedback equipment. This resembles theory of unmasking explaining recovery from paresis caused by damage in the central nervous system. Spasticity results from disruption of the inhibitory effects of the central motor system. Biofeedback training for relaxation may form neural circuits which impose negative activities on the motor output.

Prerequisites for Biofeedback Therapy

Alertness is essential for initiating biofeedback training. Patients must concentrate on the display and sound signals indicating motor activities or performance, and respond correctly to the signals during repeated sessions. Motivation is another prerequisite.^{15,48)} We can define both internal motivating factors and

external factors. The major internal factor is desire to improve functional capability. External factors include task-related feedback and praise. Biofeedback can serve provision of knowledge regarding performance and desire to continue the task. Intriguing display and sound motivate patients, especially children, for pursuits of better performance. Implication of computer game is also useful. Perceptual and/or cognitive function may be impaired in some of the patients with adventitious brain damage and cerebral palsy. Visual and auditory sensation have to be evaluated in those patients before starting biofeedback treatment. Receptive aphasia may limit the use of biofeedback. Feedback information should be simple and calibrated according to patients' ability and interest. Proprioceptive function is a clue for success in biofeedback therapy. The extent of proprioceptive loss is a factor governing treatment outcome.^{6,49)}

Clinical application of EMG biofeedback necessitates appropriate detection of motor unit activities. Therefore, it is not applicable to

severe paresis with no motor unit activity. However, careful placement of the surface electrodes may find the activity. Posture is also important for facilitating the activity in the hemiplegic muscle. Neurophysiological reaction such as association movement and synergy can be used to elicit motor unit activities. Facilitation technique is also helpful for this purpose. Indwelling electrodes must be considered for scarce motor unit activities in reinnervating muscles especially after nerve graft of anastomosis surgery.

Principles of EMG Biofeedback

An amplifier, a semi-integrator, a speaker, a visual indicator, and a sensitivity adjuster have to be installed in EMG biofeedback devices (Fig. 2). Myoelectric signals are recorded usually through bipolar leads. The amplified raw EMG signals which are quickly rising and falling across the zero axis form saw-tooth appearance on the oscilloscope. Raw EMG on the oscilloscope is not familiar to patients.

Fig. 2 Commercially available EMG biofeedback devices

[1] A typical device with a voltage meter as a visual indicator. A pair of electrodes are attached on the muscle belly of the tibialis anterior. A ground electrode is placed proximally on the knee. [2] An alternative device that has a bank of lights as a visual indicator.

Fig. 3 Rectification and semi-integration of the raw EMG signals

From top: raw EMG recorded from surface electrodes, full-rectified signals of the above EMG, and rectified and semi-integrated signals of the EMG.

Therefore, the signals are rectified and semi-integrated (**Fig. 3**) to show gross magnitude of the EMG signals which are displayed by microvoltage meters, digital displays, a bank of lights, etc. Muscle activity is illustrated as a unit of microvolt-second. There exists grossly linear relationship between rectified-integrated EMG level and the force generated isometrically.²⁰⁾

As for semi-integration or time-averaging, use of short time constant is appropriate for dynamic contraction training. The shorter the time constant, the shorter the time differences between a change in EMG and the biofeedback signal. A longer time constant is preferred for relaxation exercise. The semi-integrated signals are also fed into sound transducers which produce noises such as clicks, buzzes, and warbles. Sensitivity or gain of the amplifier is adjusted so that the signal output level of therapeutic concern can be well shown to the patients. The sound level adjuster often works as a threshold setter which modulates the transducer so as to emit sound only when the patients achieve a target level of muscle activities. Some biofeedback devices are provided with more than two sets of amplifiers, several types of signal processing, and mode selection of visual-auditory output.

Various types of surface electrodes are com-

Fig. 4 "Cross talk" from adjacent muscles

[1] Elbow flexion: voltage from the narrowly-spaced electrodes attached on the biceps muscle belly is lower than that of the widely-spaced ones. [2] Elbow extension: distant EMG activities from triceps appears in the widely-spaced electrodes attached on the biceps muscle.

mercially available. Larger electrodes are used for larger muscles such as tibialis anterior and quadriceps femoris. Electrode placement is another concern. Although bipolar lead from the muscle belly and its tendon is popular, wider spacing of electrodes causes "cross talk" originating from distant muscles. **Figure 4** demonstrates "cross talk" from the antagonist muscle. As the inter-electrode distance is made wider, the cross talk increases. Thus, narrower spacing of electrodes, both of which are attached to the muscle belly, are preferred for strengthening specific muscles although the EMG signals become lower in magnitude. On the other hand, wider spacing is used for biofeedback relaxation. It is known, likewise, that the thicker the skinfold, the larger the cross talk from adjacent muscles.

Constant electrode placement is essential to make EMG signal values comparable from session to session. Keeping constant electrode position, both patients and therapists can assess general progress of treatment. It is not often the case, but when the input matching impedance of the device is not high enough compared with that between the skin and electrodes, skin must be rubbed to reduce impedance before electrodes are attached. It is also important not to move electrode wire during training so that artifact signals can be minimized. Recent advances in technology have had a small pre-amplifier installed in the electrode to avoid such motion artifacts.³⁸⁾

Indwelling wire or needle electrodes are sometimes used in cases where no electrical activity or only scarce motor units can be detected from surface electrodes. Needle electrodes enable us to identify each motor unit as a different unit on the oscilloscope. Advantage of needle use is, therefore, that we can discriminate increase of firing frequency from recruitment of other motor units while contracting the target muscle harder. As already described, control of firing frequency can be differently trained from that of recruitment.³⁾ Both are important for strengthening. However, it is different depending upon muscles whether either of these plays a more important role to control power. It is known that EMG biofeedback training increases firing frequency rather than recruitment in the paretic muscles.⁴³⁾

EMG Biofeedback for Strengthening

Strengthening is more effectively accomplished when incorporating with EMG biofeedback.¹¹⁾ Back and quadriceps muscles are targets for strengthening in patients with chronic low back pain¹⁾ and after reconstructive ligament surgery of the knee,¹²⁾ respectively. Use of biofeedback is of benefit to strengthening of specific muscles in isolation. It is possible to strengthen vastus medialis while relaxing vastus lateralis muscles.³²⁾ This type of training can relieve osteoarthritic pain of the varus

knee.²⁷⁾

Several attempts have been made for patients with disturbance of peripheral nervous system to treat muscle weakness by use of EMG biofeedback. These include Guillain-Barre syndrome,²²⁾ facial nerve palsy,⁴⁰⁾ and peripheral nerve injury.³⁷⁾ Spinal cord injury causes loss of effective motoneurons similarly to that in peripheral nerve injury. Thus, weakened muscles innervated by non-disabled anterior horn cells at the border of the spinal lesion can be candidates for biofeedback strengthening.²⁸⁾ Biofeedback is specially important after surgical treatment of nerve anastomosis since not only strengthening but reeducation of the muscles are necessary during reinnervation. It is necessary to strengthen facial muscles while relaxing tongue muscles after hypoglossal-facial anastomosis,¹⁸⁾ and to facilitate biceps contraction without deeply breathing after intercostal-musculocutaneous anastomosis.¹⁹⁾

Biofeedback Training for Hemiplegic Patients

Footdrop, genu-recurvatum, shoulder subluxation, and reduced finger-wrist extension are major targets for biofeedback therapy in hemiplegic patients. In general, the lower extremity shows greater functional gains than the uppers.⁴⁸⁾ Although duration of hemiplegia and age at onset seem to affect the outcome,⁶⁾ it is still controversial.⁸⁾ However, patients with early moderate or late mild hemiplegia are usually selected as candidates for biofeedback therapy.⁴⁾ Level of myoelectric signals, active ROM, and muscle strength can be improved by the training of tibialis anterior.⁸⁾ Walking pattern can be also improved.²³⁾ Biofeedback information may as well be presented during walking. Use of auditory feedback alone is preferred so that the patients can pay attention to the environment and watch the foot avoid inversion. When enough dorsiflexion of the ankle is not seen, a flexor synergy pattern is utilized to activate the dorsiflexors by simultaneously flexing the knee and hip. Goniometric

feedback is effectively used to prevent the hemiplegic knee from hyperextension during the stance phase of gait cycle.²⁾

Shoulder subluxation is a problem among flaccid hemiplegic patients causing pain and edema in the hand. EMG biofeedback is applied to the upper trapezius and deltoid. The patients may be asked to shrug either the involved or both shoulders. Visual feedback using a mirror is also advised. With reduction of the scapular tilt, shoulder subluxation can be restored. Synergistic contraction of the supraspinatus, helpful to reduce shoulder subluxation, is induced by contraction of the upper trapezius.⁹⁾ EMG biofeedback in conjunction with conventional physical therapy was shown to have an additional therapeutic effect for the hemiplegic upper limb.²¹⁾ Cocontraction of the antagonists interferes with functional improvement by EMG biofeedback of the forearm extensors as well as that of the upperarm. Dual-channel EMG biofeedback equipment is useful to reduce cocontraction while enhancing the agonist contraction. Facilitation techniques, such as tapping, stretching, and stroking, are used to elicit effective contraction. Associated movement or mirror synergia, that is, the movement on the involved side associated with that on the non-involved side is also useful for enhancing volitional movements.³⁹⁾

Several experimental trials using new techniques have been introduced as to EMG biofeedback for stroke patients. Sensory stimulation was reported to improve reflex and voluntary motor function.²⁹⁾ An electrical stimulator can be incorporated in the EMG biofeedback device in which the electrical stimulator is turned on by the myoelectric signals reaching above the preset threshold. Simultaneous electrical stimulation of the monitored muscle is to enhance recovery probably induced by proprioceptive neuromuscular facilitation-like effects.^{10,15)} Triggered by the myoelectric signals, electrical stimulation of certain duration is applied to the tibialis anterior^{10,15)} or forearm extensors.³⁶⁾ Force or load monitor is another biofeedback option for stroke rehabilitation. The Krusen

Limb Load Monitor which consists of a force transducer housed within a footplate placed in the sole of a shoe is used to facilitate weight-shifting activities. A tone can be emitted when force upon the plate reaches a preset threshold.⁵⁰⁾ It is helpful to achieve symmetrical standing.⁴⁵⁾

Biofeedback Treatment for the Cerebral Palsy

Cerebral palsied children, even if they are hemiplegic, are not miniatures of the adult stroke patients. Brain plasticity in childhood is of great magnitude. Furthermore, children with disability acquire various skills as they grow and develop. It is important to notice that they are doing things, such as walking, grasping, and eating, differently from those done by normal adults. Therefore, therapists do not necessarily have to concentrate on a normal sequence or pattern of movements. Too much emphasis upon the normals may even worsen functional capability of the children.

Cerebral palsied children often have problem in lifting their heads and bringing them in line with their torsos. The problem may be ascribed to perceptual disturbance of visual-vestibular function. Audio-visual biofeedback to correct head and neck position has been introduced as a therapeutic tool. An electromechanical potentiometer, a mercury switch, or a piezo-resistive accelerometer³⁰⁾ can be utilized as a sensor of the head position that is placed in a helmet. It should be noted that posture may affect control of the head and neck.

Other Biofeedback Applications

Several reports are available as to biofeedback training for the amputee. Control of the knee joint unit in the above-knee amputee can be trained using an audio signal.¹⁴⁾ A Limb Load Monitor similar to the Krusen's is useful for establishing weight-shifting activities of elderly below-knee amputees.¹⁶⁾ Chronic low back pain is a subject for EMG biofeedback

relaxation as well as strengthening of the back muscles.¹⁾ The target muscles for relaxation include not only the paravertebral but frontalis muscle. The frontalis muscle relaxation is also accepted as a treatment of tension headaches. EMG biofeedback relaxation of the tense sternocleidomastoid muscle is used for patients with spasmodic torticollis in conjunction with contraction activation of the atrophied contralateral counterpart. The therapeutic effects are often exhibited in an all-or-none fashion early in the training.³¹⁾ There is the evidence that targetted relaxation can be obtained by EMG biofeedback of the neck muscle and some therapeutic benefit is generally maintained at follow-up.²⁵⁾

Manometric biofeedback of external anal sphincter¹³⁾ is used to treat fecal incontinence in spina bifida patients and other conditions. In general rectal sensation is a key determinant of the outcome.⁴⁴⁾ The procedure is also effective for urinary incontinence. This type of biofeedback is considered as the sensori-motor retraining. No measurable changes in anal squeeze, bladder capacity, or rectal-bladder sensory threshold were shown by the training in stroke patients with urinary incontinence³⁵⁾ as well as that in spina bifida patients with fecal incontinence.³³⁾ EMG biofeedback of the sphincter is another option for biofeedback. A swallowing problem in patients with upper motor neuron lesion⁴²⁾ or status post oropharyngeal surgery⁷⁾ may be a recent focus of biofeedback treatment by use of manometry, EMG, or electroglottography. The evidence for efficacy is marginal at best in other applications of biofeedback modalities. Skin temperature biofeedback for vascular headache and Raynaud disease, blood pressure for hypertension or orthostatic hypotension, and electroencephalography for insomnia are among those.

Controversy over Efficacy of Biofeedback Treatment

Outcome of biofeedback therapy is often compared with that of conventional physical

therapy. Controversy exists as to superiority of biofeedback to physical therapy alone in some areas of clinical application. Cost-effectiveness is often a matter of concern in the United States. When hot packs and/or mild analgesics are as effective as biofeedback relaxation for musculoskeletal pain, choice of biofeedback should be abandoned for the sake of the cost.

Use of EMG biofeedback for stroke patients is also controversial especially as regards application to the upper extremity. It is obvious, however, for the patients to better control their paretic limbs with biofeedback signals.⁵⁾ However, increase or decrease of EMG signals revealed by the biofeedback equipment alone is not an appropriate indicator of therapeutic efficacy. It should be evaluated in terms of changes in functional capability. Considering that the ultimate goal is to control their limbs without biofeedback, outcome should be measured without biofeedback instrumentation. It is also important to show improvement of function long after treatment sessions. Meta-analysis (analysis of analyses previously done) is a recent fashion to evaluate a controversial efficacy of therapeutic modalities. It showed efficacy of EMG biofeedback therapy for the hemiplegic patients,⁴¹⁾ while it did not at all in some report,¹⁷⁾ or another focusing only upon the upper extremity did not reveal superiority of the EMG biofeedback.³⁶⁾

Several things have to be considered for future research for biofeedback treatment for stroke patients as was addressed by Wolf.⁴⁷⁾ Patients should be grouped according to the precise location and size of the lesion in the brain and also according to whether the patients are in acute or chronic care phase. Stroke patients receiving biofeedback are matched to a group that receives an alternative intervention. A separate design of study is necessary to assess efficacy of biofeedback training among patients with proprioceptive deficits. A specific biofeedback training strategy and an instrumentation used have to be delineated. Constant electrode placement is essential for the study of EMG biofeedback. Assessments of

efficacy are preferably done by independent clinical evaluators in different environment that differs from the treatment site. Prolonged follow-up assessments using the identical evaluation protocol are also to be done. Multiple clinical facilities are advised to engage in a common project using the same protocol.

References

- 1) Asfour SS, Khalil TM, Waly SM, Goldberg ML, Rosomoff RS, Rosomoff HL : Biofeedback in back muscle strengthening. *Spine* 1990 ; **15** : 510-513
- 2) Basaglia N, Mazzini N, Boldrini P, Bacciglieri P, Contenti E, Ferraresi G : Biofeedback treatment of genu-recurvatum using an electromyographic device with an acoustic signal : One-year follow-up. *Scand J Rehabil Med* 1989 ; **21** : 125-130
- 3) Basmajian JV : Control and training of individual motor units. *Science* 1963 ; **141** : 440-441
- 4) Basmajian JV, Gowland C, Brandstater ME, Swanson L, Trotter J : EMG feedback treatment of upper limb in hemiplegic stroke patients: pilot study. *Arch Phys Med Rehabil* 1982 ; **63** : 613-616
- 5) Bate PJ, Matyyas TA : Negative transfer of training following brief practice of elbow tracking movements with electromyographic feedback from spastic antagonists. *Arch Phys Med Rehabil* 1992 ; **73** : 1050-1058
- 6) Brudny J, Korein J, Grynbaum BB, Belandres PV, Gianutsos JG : Helping hemiparetics to help themselves. Sensory feedback therapy. *JAMA* 1979 ; **241** : 814-818
- 7) Bryant M : Biofeedback in the treatment of a selected dysphagic patient. *Dysphagia* 1991 ; **6** : 140-144
- 8) Burnside IG, Tobias S, Bursill D : Electromyographic feedback in the remobilization of stroke patients: a controlled trial. *Arch Phys Med Rehabil* 1982 ; **63** : 217-222
- 9) Chino N : Biofeedback treatment in rehabilitation medicine. *Prog Med (Jpn)* 1981 ; **116** : 376-382
- 10) Cozean CD, Pease W, Hubbell SL : Biofeedback and functional electric stimulation in stroke rehabilitation. *Arch Phys Med Rehabil* 1988 ; **69** : 401-405
- 11) Croce RV : The effects of EMG biofeedback on strength acquisition. *Biofeedback Self Regul* 1986 ; **11** : 299-310
- 12) Draper V, Ballard L : Electrical stimulation versus electromyographic biofeedback in the recovery of quadriceps femoris muscle function following cruciate ligament surgery. *Phys Ther* 1991 ; **71** : 455-464
- 13) Engel BT, Nikoomanesh P, Schuster MM : Operant conditioning of rectosphincteric responses in treatment of fecal incontinence. *N Engl J Med* 1974 ; **290** : 646-649
- 14) Fernie G, Holden J, Soto M : Biofeedback training of knee control in the above-knee amputee. *Am J Phys Med* 1978 ; **57** : 161-166
- 15) Fields RW : Electromyographically triggered electric stimulation for chronic hemiplegia. *Arch Phys Med Rehabil* 1987 ; **68** : 407-414
- 16) Gauthier-Gagnon C, St. Pierre D, Drouyn G, Riley E : Augmented sensory feedback in the early training of standing balance of below-knee amputees. *Physiother Can* 1986 ; **38** : 137-142
- 17) Glanz M, Klawasky S, Stason W, Berkey C, Shah N, Phan H, Chalmer TC : Biofeedback therapy in poststroke rehabilitation: a meta-analysis of randomized controlled trials. *Arch Phys Med Rehabil* 1995 ; **76** : 508-515
- 18) Hammerschlag PE, Brudney J, Casumano R, Cohen NL : Hypoglossal-facial nerve anastomosis and electromyographic feedback rehabilitation. *Laryngoscope* 1987 ; **97** : 705-709
- 19) Hara T, Akasaka Y, Hoshino Y, Natsuyama Y, Tsuyama N, Nagano A, Takahashi M, Yagi I, Tachibana S, Ochiai N, Sugioka H : Audio-visual feedback training after intercostal nerve crossing to musculocutaneous nerve for the root avulsion injury of the brachial plexus. *Orthopedics (Jpn)* 1986 ; **32** : 1562-1566
- 20) Heckathorne CW, Childress DS : Relationships of the surface EMG to the force, length, velocity, and contraction rate of the cineplastic human biceps. *Am J Phys Med* 1981 ; **60** : 1-17
- 21) Inglis J, Donald MW, Monga TN, Sproule M, Young ME : Electromyographic biofeedback and physical therapy of hemiplegic upper limb. *Arch Phys Med Rehabil* 1984 ; **65** : 755-759
- 22) Ince LP, Leon MS : Biofeedback treatment of upper extremity dysfunction in Guillain-Barre syndrome. *Arch Phys Med Rehabil* 1986 ; **67** : 30-33
- 23) Intiso D, Santilli V, Grasso MG, Rossi R, Caruso I : Rehabilitation of walking with electromyographic biofeedback in foot-drop after stroke. *Stroke* 1994 ; **25** : 1189-1192
- 24) Jacobson E : Electrical measurements concerning muscular contraction (touns) and cultivation of relaxation in man. *Am J Physiol* 1933 ; **1207** : 230-248
- 25) Jahanshahi M, Sartory G, Marsden CD : EMG biofeedback treatment of torticollis: a controlled outcome study. *Biofeedback Self Regul* 1991 ; **16** : 413-448
- 26) Kawato M, Gomi M : A computational model of four regions of the cerebellum based on feedback-error learning. *Biol Cybern* 1992 ; **68** : 95-103

- 27) King AC, Ahles TA, Martin JE, White R: EMG biofeedback-controlled exercise in chronic arthritic pain. *Arch Phys Med Rehabil* 1984; **65**: 341-343
- 28) Klose KJ, Needham BM, Schmidt D, Broton JG, Green BA: An assessment of the contribution of electromyographic biofeedback as an adjunct therapy in physical training of spinal cord injured persons. *Arch Phys Med Rehabil* 1993; **74**: 453-456
- 29) Levin MF, Hiu-Chan CWY: Relief of hemiparetic spasticity by TENS is associated with improvement in reflex and voluntary motor function. *Electroenceph Clin Neurophysiol* 1992; **85**: 131-142
- 30) Leiper CI, Miller A, Lang J, Herman R: Sensory feedback for head control in cerebral palsy. *Phys Ther* 1981; **61**: 512-518
- 31) Leplow B: Heterogeneity of biofeedback training effects in spasmodic torticollis: a single-case approach. *Behav Res Ther* 1990; **28**: 359-365
- 32) LeVeau BF, Rogers C: Selective training of the vastus medialis muscle using EMG biofeedback. *Phys Ther* 1980; **60**: 1410-1415
- 33) Loening-Baucke V, Desch L, Wolraich M: Biofeedback training for patients with myelomeningocele and fecal incontinence. *Dev Med Child Neurol* 1988; **30**: 781-790
- 34) Mandel AR, Nymark JR, Balmer SJ, Grinnell DM, O'Rian MD: Electromyographic versus rhythmic positional biofeedback in computerized gait training with stroke patients. *Arch Phys Med Rehabil* 1990; **71**: 649-654
- 35) Middaugh SJ, Whitehead WE, Burgio KL, Engel BT: Biofeedback in treatment of urinary incontinence in stroke patients. *Biofeedback Self Regul* 1989; **14**: 3-19
- 36) Moreland J, Thomson MA: Efficacy of electromyographic biofeedback compared with conventional physical therapy for upper-extremity function in patients following stroke: a research overview and meta-analysis. *Phys Ther* 1994; **74**: 534-547
- 37) Nakatsuchi Y, Saitoh H, Hosaka M, Uchiyama S, Simokawa K: Application of biofeedback training for traumatic brachial plexus palsy treated by nerve repair. *J Jpn Soc Surg Hand (Jpn)* 1987; **4**: 190-194
- 38) Nishimura S, Tomita Y, Horiuchi T: Clinical application of an active electrode using an operational amplifier. *IEEE Trans Biomed Eng* 1992; **39**: 1096-1099
- 39) Rathkolb O, Baykoushev St, Baykousheva V: Myobiofeedback in motor reeducation of wrist and fingers after hemispherical stroke. *Electromyogr Clin Neurophysiol* 1990; **30**: 89-92
- 40) Ross B, Nedzelski JM, McLean JA: Efficacy of feedback training in long-standing facial nerve palsy. *Laryngoscope* 1991; **101**: 744-750
- 41) Schleenbaker RE, Mainous AG: Electromyographic biofeedback for neuromuscular reeducation in the hemiplegic stroke patients: a meta-analysis. *Arch Phys Med Rehabil* 1993; **74**: 1301-1304
- 42) Schultz JL, Perlman AL, VanDaele DJ: Laryngeal movement, oropharyngeal pressure, and submental muscle contraction during swallowing. *Arch Phys Med Rehabil* 1994; **75**: 183-188
- 43) Stein RB, Brucker BS, Ayyar DR: Motor units in incomplete spinal cord injury: electrical activity, contractile properties and the effects of biofeedback. *J Neurol Neurosurg Psychiat* 1990; **53**: 880-885
- 44) Wald A: Biofeedback for neurologic faecal incontinence: rectal sensation is a determinant of outcome. *J Pediatr Gastroenterol Nutr* 1983; **2**: 302-306
- 45) Wannstedt GT, Herman R: Use of augmented sensory feedback to achieve symmetrical standing. *Phys Ther* 1978; **58**: 553-559
- 46) Winstein CJ, Schmidt RA: Reduced frequency of knowledge of results enhances motor skill learning. *J Exp Psychol [Learn Mem Cogn]* 1990; **10**: 677-691
- 47) Wolf SL: Electromyographic biofeedback application to stroke patients: A critical review. *Phys Ther* 1983; **63**: 1448-1455
- 48) Wolf SL, Baker MP, Kelly JL: EMG biofeedback in stroke: effect of patient characteristics. *Arch Phys Med Rehabil* 1979; **60**: 96-103
- 49) Wolf SL, Baker MP, Kelly JL: EMG biofeedback in stroke: a one-year follow-up of the effect on patient characteristics. *Arch Phys Med Rehabil* 1980; **61**: 351-355
- 50) Wolf SL, Hudson JE: Feedback signal based upon force and time delay. *Phys Ther* 1980; **60**: 1289-1290